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灌溉方式和施氮量对直播稻氮素、水分利用及产量的影响*

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摘　要: 为研究不同灌溉方式和施氮量对直播稻的光合生产、干物质积累、氮素利用、水分利用和稻谷产量的影响, 采用裂裂区试验设计, 主区因素为品种: ‘德香 4103’和‘金农丝苗’, 副区因素为 3 种灌溉方式: 浅水灌溉、轻干湿交替灌溉和重干湿交替灌溉, 副副区因素为 4 个施氮量: 0 kg(N)·hm^{-2}、120 kg(N)·hm^{-2}、180 kg(N)·hm^{-2}、240 kg(N)·hm^{-2}, 分析测定直播稻的干物质积累量、氮素积累量和利用率、水分利用率和产量等指标。结果表明: 灌溉方式和施氮量对直播稻氮素利用和产量形成的影响存在显著的互作效应。与浅水灌溉相比, 轻干湿交替灌溉处理下‘德香 4103’和‘金农丝苗’抽穗期剑叶净光合速率、拔节—抽穗期干物质积累量、抽穗期和成熟期氮素积累量、结实期茎叶氮素转运量、成熟期籽粒中氮素积累量、氮素农艺效率和氮肥回收效率显著增加; 抽穗期叶面积指数、拔节前干物质积累量、成熟期茎叶氮素积累量显著降低。施氮量对‘德香 4103’和‘金农丝苗’氮素积累量、氮素利用效率、产量的影响存在差异。浅水灌溉处理中, 与无氮相比, ‘德香 4103’和‘金农丝苗’施氮后产量分别提高 31.79%~48.77%和 29.72%~45.36%; 施氮量超过 180 kg·hm^{-2} 后, ‘德香 4103’的产量、干物质积累量、氮素农艺效率和氮肥回收效率显著下降, 而‘金农丝苗’相应指标却无显著变化。轻干湿交替灌溉处理中, 与无氮相比, ‘德香 4103’和‘金农丝苗’施氮后产量分别提高 32.58%~61.10%和 36.49%~48.45%; 施氮量超过 180 kg·hm^{-2} 后‘德香 4103’的产量无显著变化, 干物质积累量、抽穗期和成熟期氮素积累量、氮肥回收效率均显著增加, 氮素农艺效率显著下降, ‘金农丝苗’的产量和干物质积累量无显著变化, 抽穗期和成熟期氮素积累量、氮素农艺效率和氮肥回收效率显著降低。重干湿交替灌溉处理中, 与无氮相比, ‘德香 4103’和‘金农丝苗’施氮后产量分别提高 37.01%~42.88%和 30.11%~42.63%; 施氮量超过 180 kg·hm^{-2} 后, ‘德香 4103’和‘金农丝苗’的产量无显著变化, 氮素积累量显著增加, ‘金农丝苗’氮素积累量无显著增加, 两个品种氮素农艺效率和氮肥回收率均显著降低。综上所述, 轻干湿交替灌溉更适合于直播稻高产、节水、高效栽培, 其中‘德香 4103’产量在轻干湿交替灌溉下施纯氮 240 kg·hm^{-2} 处理最高, ‘金农丝苗’产量在轻干湿交替灌溉下施纯氮 180 kg·hm^{-2} 处理最高。

关键词: 水稻; 直播; 灌溉方式; 施氮量; 干物质积累; 氮素利用; 水分利用; 产量

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Effects of irrigation management and nitrogen rate on nitrogen and water utilization and grain yield of direct-seeded rice

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Abstract: Direct-seeded rice has advantages of less labor, lower labor strength and cost. But it meantime has different development characteristics from the transplanted rice. It is necessary to investigate the cultivation and growth of direct-seeded rice. In this study a field experiment was conducted to investigate the effects of irrigation managements and nitrogen application rates on nitrogen and water utilization and yield of direct-seeded rice. In the experiment, a split-split plot design was set with rice varieties ('Dixiang4103' and 'Jinnongsimiao') as the main factor, irrigation managements (shallow water irrigation, alternate irrigation with wetting and moderate drying, alternate irrigation with wetting and severe drying) as the sub-plot factor, and N rate (0, 120 kg·hm^{-2}, 180 kg·hm^{-2} and 240 kg·hm^{-2}) as the split-split plot factor. The photosynthetic rate, dry matter accumulation, nitrogen utilization, water utilization and yield of direct-seeded rice were measured at different growth stages. There was a significant interaction between irrigation management and N rate on nitrogen utilization, water utilization and yield of direct-seeded rice. Compared with the shallow water irrigation, the net photosynthetic rate at jointing stage, dry matter accumulation at jointing-heading stage, nitrogen accumulation at heading and mature stages, nitrogen transport amounts of stems and leaves at mature stage, nitrogen accumulation of grains at maturity stage, nitrogen agronomic efficiency and nitrogen fertilizer recovery efficiency were significantly increased in the alternate irrigation with wetting and moderate drying; however, the leaf area index at heading stage, dry matter accumulation before jointing and nitrogen accumulation in stems and leaves at mature stage were significantly decreased. The effect of N rates on nitrogen accumulation, nitrogen utilization efficiency and yield of 'Dexiang 4103' and 'Jinnongsimiao' were different. Under the shallow water irrigation, compared with nitrogen free treatment, the yields of 'Dexiang 4103' and 'Jinnongsimiao' increased by 31.79%–48.77%, 29.72%–45.36%, respectively, under treatments of applying nitrogen fertilizer. But as N rate was more than 180 kg·hm^{-2}, with the N rate increase, the yield, dry matter accumulation, nitrogen agronomic efficiency and nitrogen fertilizer recovery efficiency of 'Dexiang 4103' was significantly decreased and the corresponding indicators of 'Jinnongsimiao' were not significantly changed. Under the alternate irrigation with wetting and moderate drying, compared with nitrogen free treatment, the yields of 'Dexiang 4103' and 'Jinnongsimiao' increased by 32.58%–61.10%, 36.49%–48.45%, respectively, under treatments of applying nitrogen fertilizer. as When N rate was more than 180 kg·hm^{-2}, for 'Dexiang 4103', the yield was not significantly changed, the dry matter accumulation, nitrogen accumulation at heading and maturity stages, nitrogen fertilizer recovery efficiency significantly increased, the nitrogen agronomic efficiency decreased with the increase of N rate. For 'Jinnongsimiao', the yield, dry matter accumulation not changed significantly, and the nitrogen accumulation at heading and maturity stages, nitrogen agronomic efficiency, nitrogen fertilizer recovery efficiency of 'Jinnongsimiao' were significantly decreased. Under the alternate irrigation with wetting and severe drying, compared with nitrogen free treatment, the yields of 'Dexiang 4103' and 'Jinnongsimiao' increased by 37.01%–42.88%, 30.11%–42.63%, respectively, under the treatments of applying nitrogen fertilizer. When N rate was more than 180 kg·hm^{-2}, the yield of two cultivars was not changed significantly, their nitrogen agronomic efficiency and nitrogen fertilizer recovery efficiency significantly decreased with the N rate increase. The nitrogen accumulation of 'Dexiang 4103' increased significantly and that of 'Jinnongsimiao' was not changed significantl with N rate increase. In summary, alternate irrigation with wetting and moderate drying was more suitable for high yield, water saving and high efficiency cultivation of direct-seeded rice, the highest yields of 'Delixiang4103' and 'Jinnongsimiao' were found under N rates of 240 kg·hm^{-2} and 180 kg·hm^{-2}, respectively.

Keywords: Rice; Direct seeding; Irrigation management; Nitrogen rate; Dry matter accumulation; Nitrogen utilization; Water utilization; Yield

干旱是影响水稻丰产性最为突出的因素之一，水稻节水栽培技术和抗旱能力提升被广大科研工作者所重视[1-5]。近年来，干湿交替灌溉技术在中国和东南亚国家得到快速推广和延伸[6]。适度的水分胁迫有利于提高土壤通气性，增加土壤细菌、放线菌活性和数量，促进水稻根系生长[7]，提高土壤中部分酶活性及水稻根系氧化力和渗透调节物质含量[4]，促进水稻对轻度水分胁迫产生适应性变化，同时提高叶片气孔导度、蒸腾速率和净光合速率[8]，提高水稻产量[9]，降低耗水量，提高水分生产率，改善稻米品质[10]。以往对干湿交替灌溉技术方面的研究缺少水分精确化控制，加之该技术在不同生态区的适应程度也不尽一致，所以使得其对产量的影响结果并未达成共识[1,3,11]。为此，在本试验区进一步开展干湿交替灌溉过程中水分控制程度研究能够为水稻节水稳产，甚至增产提供理论依据。

氮是水稻正常生长发育过程中必不可少的元素，不同的氮肥施用方式[12]、施用量[13]、氮素形态[14]等均会对氮肥利用产生不同影响。水、氮在作物生产中往往是相互制约、相互协同的，水氮互作在移栽稻上研究较多，主要集中于干物质生产、稻米品质[10]、生理性状[15-16]、产量、氮代谢酶、氮、磷、钾的吸收[17]等方面，主要结论是：水、氮肥对水稻产量、部分生理指标、氮吸收利用、氮代谢酶、根系特征、干物质量

等有显著的互作效应[15,18-19]。近年来，随着栽培方式多样化，直播稻推广逐年受到重视，直播面积、直播比例在不同地区均有较大发展。直播水稻具有用工少、劳动强度低、成本低等优点，顺应了轻简化栽培发展的需求，且与移栽稻相比，直播稻播期推迟，营养生长期缩短，在利用温光资源表现出一些不同的生育特征[20]。因此，加强对直播稻栽培研究显得十分重要。从播期、施肥、水分、氮肥运筹等方面对直播稻的产量、氮素吸收、养分积累利用、品质、光合特性、生理指标等开展了一系列研究[20-23]，但直播稻生产中水、氮互作效应鲜见报道。本研究重在探索水氮互作对直播稻光合物质及干物质生产积累、产量及其构成因素的影响，以及直播稻的氮素吸收利用特点，以探索直播稻水肥调控机理，明确最优水氮管理模式，为高效养分管理和发展节水丰产型直播稻生产提供理论基础和实践依据。

1 材料与方法

1.1 试验设计

试验于 2013 年在四川省德阳市绵竹市孝德镇金星村进行。试验田块为砂壤土，排灌方便，前茬为冬闲田。土壤有机质为 23.40 $g\cdot kg^{-1}$、速效氮 61.01 $mg\cdot kg^{-1}$、速效磷 10.41 $mg\cdot kg^{-1}$、速效钾 70.42 $mg\cdot kg^{-1}$、全氮 1.70 $g\cdot kg^{-1}$、全磷 0.82 $g\cdot kg^{-1}$、全钾 18.32 $g\cdot kg^{-1}$。

试验采用 3 因素裂区试验设计，主区为品种，副区为灌溉方式，副副区为施氮量。2 个供试品种：‘德香 4103’(超级稻，全生育期 150 d)和‘金农丝苗’(超级稻，全生育期 142 d)。3 种灌溉方式：浅水灌溉(W1)，2 叶 1 心至成熟期保持 1~3 cm 水层；轻干湿交替灌溉(W2)，播种后第 64 d 开始，每次灌水 2~3 cm，当土壤水势(ψ_{soil})为−15 kPa 时(用中国科学院南京土壤研究所生产的真空表式土壤负压计测定土壤水势)，再灌水 2~3 cm，如此循环；重干湿交替灌溉(W3)，播种后 64 d 起每次灌水 2~3 cm，当土壤水势(ψ_{soil})为−30 kPa 时，再灌水 2~3 cm，如此循环。4 个施氮量：0 $kg(N)\cdot hm^{-2}$(N0)、120 $kg(N)\cdot hm^{-2}$(N120)、180 $kg(N)\cdot hm^{-2}$(N180)、240 $kg(N)\cdot hm^{-2}$(N240)。

4 月 5 日采用水直播，播种时进行人工划行均匀播种(芽谷)，播种量折干种为 22.5 $kg\cdot hm^{-2}$，播种行距为 30 cm。播后出苗前进行化学除草，3 叶 1 心期进行人工定苗，‘德香 4103’和‘金农丝苗’定植密度分别为 3.0×10^5 株$\cdot hm^{-2}$ 和 4.5×10^5 株$\cdot hm^{-2}$。氮、磷、钾肥为尿素、过磷酸钙、氯化钾。氮肥中基肥占 30%，断奶肥(1 叶 1 心)占 20%，分蘖肥(4 叶 1 心)占 20%，穗肥(倒 3 叶)占 30%。P_2O_5 和 K_2O 施用量分别为 90 $kg\cdot hm^{-2}$ 和 180 $kg\cdot hm^{-2}$，其中磷肥全作基肥施用，钾肥分基肥和拔节肥两次施用，各占 50%。小区面积 5 m×3 m=15 m^2，3 次重复，小区间作埂(40 cm 宽)覆膜，其余田间管理同当地大面积生产田块。

1.2 测定项目与方法

1.2.1 水分利用率

记录全生育期各小区的降雨量，记录每一次灌溉量和排水量，计算水分利用率。

1.2.2 干物质积累和植株叶面积指数(LAI)

于拔节期、抽穗期及成熟期，按各小区平均茎蘖数各取代表性植株1行(长度为1m)，去根后分为叶、茎鞘、穗，于105 ℃杀青30 min，75 ℃烘至恒重，后称重。其中，在抽穗期用美国生产的CID-203叶面积仪测定叶面积，并计算叶面积指数(LAI)。

1.2.3 植株氮积累量

利用1.2.2中的干物质样品，粉碎后过60目筛，采用H_2SO_4-H_2O_2消化，采用半微量凯氏定氮法测定各部位含氮量，计算植株氮积累量。

1.2.4 净光合速率

于抽穗期，选择晴天上午 9:00—11:30，用美国生产的 LI-6400 便携式光合仪，测定剑叶光合速率(P_n)，人工控制条件：CO_2 浓度为 400 $\mu mol\cdot mol^{-1}$，温度为 30 ℃，光照强度为 1 000 $\mu mol\cdot m^{-2}\cdot s^{-1}$。每小区测定 5 片，重复测定 3 次。

1.2.5 考种与计产

于成熟期每小区调查 2 行(每行长度为 4 m)稻株穗数，计算单位面积穗数；并取接近于平均穗数的植株 1 行(长度为 2 m)，考查穗数、实粒数、空壳数、结实率、千粒重等产量构成因素。去边行及杂株按实收面积计产。

1.2.6 参数计算

氮素收获指数=成熟期单位面积植株籽粒氮素积累量/植株氮素总积累量 (1)

结实期茎鞘(叶)氮素表观转移量(kg)=抽穗期茎鞘(叶)氮积累量−成熟期茎鞘(叶)氮积累量 (2)

结实期氮素表观转移率(%)=茎鞘(叶)氮素表观转移量/抽穗期茎鞘(叶)氮积累量×100% (3)

结实期转移的氮对籽粒的贡献率(%)=结实期茎叶氮素表观转移总量/成熟期籽粒氮积累量×100% (4)

氮素干物质生产效率(%)=单位面积干物质量/单位面积植株氮积累量×100% (5)

氮素稻谷生产效率(%)=单位面积籽粒产量/单位面积植株氮积累量×100% (6)

氮肥农艺效率($kg\cdot kg^{-1}$)=(施氮肥区产量–不施氮肥区产量)/施氮量 (7)

氮肥吸收利用效率(%)=(施氮区植株总吸氮量–空白区植株总吸氮量)/施氮量×100% (8)

水分利用率($kg\cdot kg^{-1}$)=籽粒产量($kg\cdot hm^{-2}$)/(降雨量+灌水量–排水量)($kg\cdot hm^{-2}$) (9)

1.3 数据分析用

采用 DPS 7.05 软件进行试验数据分析，最小显著差法 LSD 检验平均数，Origin 2017 作图。

2 结果与分析

2.1 灌溉方式和施氮量对直播稻产量及其构成的影响

表 1 可见，直播条件下水稻品种间产量差异极显著，表现为常规稻品种‘金农丝苗’显著高于杂交稻品种‘德香 4103’，有效穗、群体颖花量及结实率等产量性状的显著提高是‘金农丝苗’在直播条件下表现出明显产量优势的关键。同时，各水氮处理对不同品种产量的影响均达极显著水平，且互作效应极显著。其中，‘德香 4103’产量以 W2N240 处理最高，‘金农丝苗’产量以 W2N180 处理最高。灌溉方式仅对有效穗和结实率的影响极显著，表现为有效穗随灌水量的减少而显著降低，W3 处理结实率显著低于 W1、W2 处理。施氮量对各产量性状的影响均达极显著，表明施氮量对直播稻每穗粒数、群体颖花量及千粒重的影响高于灌溉方式，但其与品种对有效穗的影响存在显著的互作效应，品种和灌溉方式对每穗粒数的影响存在极显著的互作效应。

除有效穗随施氮量的增加而显著提高外，对其余产量构成因素的影响因品种、灌溉方式而异。‘德香 4103’在常规灌溉方式下随施氮量的增加，每穗粒数和结实率先增加后减少，群体颖花量呈增加趋势，千粒重无显著变化；在轻、重干湿交替灌溉方式下随施氮量的增加，每穗粒数和群体颖花量呈增加趋势，而结实率和千粒重则反之。‘金农丝苗’在常规灌溉方式下随施氮量的增加，每穗粒数减少，群体颖花量增加，千粒重先增加后减少；在轻干湿交替灌溉方式下，每穗粒数和群体颖花量先增加后减少，千粒重降低；在重干湿交替灌溉方式下，每穗粒数减少，群体颖花量先增加，千粒重无显著变化。此外，不同灌溉方式下施氮量对该品种的结实率影响不显著。

表 1 灌溉方式和施氮量对不同品种直播稻产量及产量构成的影响

Table 1 Effects of irrigation managements and nitrogen rates on yield and its components of different varieties of direct-seeded rice

品种 Variety	灌溉方式 Irrigation management	施氮量 Nitrogen rate ($kg\cdot hm^{-2}$)	有效穗数 Effective panicle number ($\times10^4\ hm^{-2}$)	每穗粒数 Number of grains per panicle	群体颖花量 Spikelets amount ($\times10^4\ hm^{-2}$)	结实率 Seed-setting rate (%)	千粒重 1000-grain weight (g)	产量 Yield ($t\cdot hm^{-2}$)
德香 4103 Dexiang 4103	W1	0	164.75±9.13f	141.08±3.978e	23.24±1.36f	86.91±1.49e	31.37±0.36ab	6.48±0.34f
		120	203.30±3.88cd	158.96±3.20bc	32.31±0.50c	85.82±1.13cd	30.97±0.33abc	8.54±0.26bc
		180	205.25±6.51cd	172.41±2.39a	35.38±0.98b	85.06±1.08ab	31.19±0.38abc	9.64±0.40a
		240	224.70±5.56a	159.29±2.27bc	35.79±0.67b	80.15±1.78f	30.89±0.26abc	8.95±0.25b
	平均 Average		199.50	157.94	31.68	84.49	31.11	8.40
	W2	0	152.40±3.23g	135.55±6.13ef	20.66±1.32g	86.62±0.70a	31.74±1.30a	6.17±0.11f
		120	198.90±7.10de	152.62±4.33c	30.34±0.62cd	86.58±1.25bc	31.19±0.22abc	8.18±0.21cd
		180	204.14±6.28bc	178.00±5.17ab	36.41±2.17b	85.28±0.67e	31.23±0.35abc	9.59±0.19a
		240	219.85±4.19ab	170.19±5.85a	37.40±0.74a	82.24±0.65e	30.45±0.28bc	9.94±0.25a
	平均 Average		193.88	159.09	31.20	85.18	30.29	8.47
	W3	0	145.55±6.98g	126.77±9.27f	18.41±0.46h	84.98±1.88a	31.34±0.17ab	5.62±0.36g
		120	193.00±2.38e	142.77±6.85de	27.55±1.26e	83.97d±0.75e	30.16±1.12bc	7.70±0.14e
		180	196.85±6.89de	152.18±2.95cd	29.95±0.48d	82.05±0.94ef	29.86±0.55c	7.75±0.21de
		240	212.41±3.98cd	149.86±5.97c	31.82±0.75cd	77.68±1.40g	29.79±0.45c	8.03±0.23de
	平均 Average		186.97	142.89	26.93	82.17	30.29	7.27
金农丝苗 Jinnongsimiao	W1	0	252.30±21.69fg	131.77±7.99c	33.36±4.76d	88.50±0.58abc	21.83±0.55bcd	6.46±0.15g
		120	285.70±3.61cde	149.20±5.12abc	42.62±1.39c	88.07±0.81ab	21.97±0.51abcd	8.38±0.18ef
		180	298.20±13.56cd	152.48±1.73abc	45.46±1.73c	88.78±1.51abc	22.86±0.94a	9.24±0.25bc
		240	324.80±1.14a	148.77±5.37abc	48.31+1.70a	89.82±0.27ab	21.05±0.39d	9.39±0.08abc
	平均 Average		290.25	145.55	42.44	88.79	21.93	8.40
	W2	0	241.05±1.42gh	135.95±1.92bc	32.78±0.48d	89.46±1.03ab	21.97±0.34abcd	6.44±0.21g
		120	281.45±14.50de	155.38±0.96abc	43.75±2.51c	88.47±0.43abc	22.60±0.36abc	8.79±0.12de
		180	292.05±8.68cd	165.02±10.58a	48.22±4.13a	88.32±1.08a	21.94±0.06abcd	9.56±0.28a

	240	319.10±10.44ab	162.67±3.18abc	51.90±1.64a	88.63±1.20abc	21.64±0.93cd	9.15±0.23ab
	平均 Average	283.41	154.76	44.16	88.72	22.04	8.49
W3	0	231.25±5.23h	132.91±1.42abc	30.73±0.84	87.61±2.27e	22.64±0.80ab	6.31±0.15g
	120	268.95±2.65ef	151.82±5.51a	40.83±1.71c	87.54±1.20cd	22.01±0.19abcd	8.21±0.15f
	180	287.85±6.26cd	156.82±7.57a	45.16±2.90b	86.69±1.02bc	21.83±0.45bcd	8.75±0.23de
	240	310.86±5.84bc	150.07±1.55ab	46.64±0.46a	86.26±1.56de	21.79±0.48bcd	9.00±0.11cd
	平均 Average	274.72	147.90	40.84	87.03	22.06	8.07
F 值 *F*- value	品种 Variety (V)	1695.64**	0.15	2362.21**	126.99**	6139.46**	8.57**
	灌溉方式 Irrigation management (I)	15.73**	2.10	2.38	27.83**	1.42	177.12**
	施氮量 Nitrogen rate (N)	233.02**	25.31**	72.40**	33.15**	5.95**	456.12**
	V × I	0.22	20.91**	2.78	2.13	2.48	37.50**
	V × N	3.91*	2.30	0.13	37.47**	2.38	0.05
	I × N	1.00	0.60	0.53	10.32**	1.96	6.75**
	V × I × N	0.38	0.96	0.31	17.18**	0.66	3.51*

W1: 2 叶 1 心至成熟期保持 1~3 cm 水层; W2: 播种后 64 d 至成熟期, 每次灌水 2~3 cm, 当土壤水势(ψ_{soil})为−15 kPa 时, 再灌水 2~3 cm, 如此循环; W3: 播种后 64 d 至成熟期, 每次灌水 2~3 cm, 当土壤水势(ψ_{soil})为−30 kPa 时, 再灌水 2~3 cm, 如此循环。同列不同小写字母表示同一品种不同灌溉方式和施氮量组合差异显著(P<0.05)。*和**分别表示在 0.05 和 0.01 水平上差异显著。W1: soil surface water layer was kept at 1−3 cm from 2.1 leaves to maturity; W2: soil surface water layer was added to 2−3 cm when the soil water potential (ψ_{soil}) reached −15 kPa from 64 days after sowing to mature stage; W3: soil surface water layer was added to 2−3 cm when the soil water potential (ψ_{soil}) reached −30 kPa from 64 days after sowing to mature stage. Different lowercases letters in the same column indicate significant differences at 0.05 level among different interaction combinations of irrigation managements and nitrogen rates of a variety. * and ** mean significant difference at 0.05 and 0.01 levels, respectively.

2.2 灌溉方式和施氮量对直播稻抽穗期光合物质生产的影响

灌溉方式和施氮水平均显著影响直播稻抽穗期叶面积指数(图 1), 各品种 LAI 随灌水量的降低而显著减少, 随施氮水平的提高而显著增加。灌溉方式和施氮水平对直播稻品种抽穗期剑叶光合速率的影响因品种而异。‘德香 4103’表现为剑叶光合速率随灌水量的降低先增后减, 随施氮量的增加而提高; 而‘金农丝苗’在两种交替灌溉方式下增加施氮量均能显著提高抽穗期剑叶光合速率(图 2)。这表明灌溉方式和施氮水平对两个直播稻品种光合生产的影响存在差异。

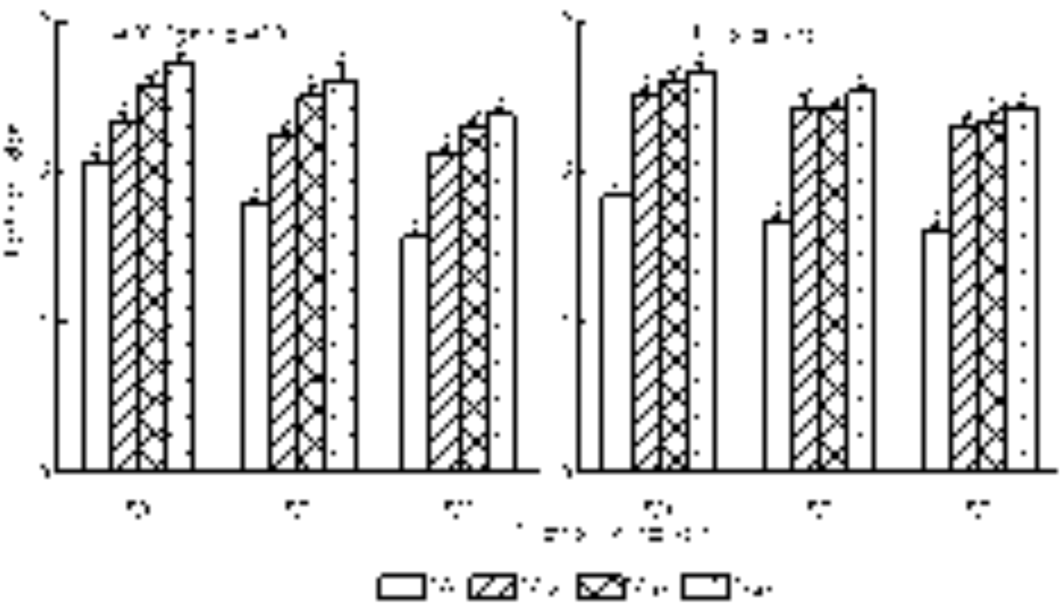

图 1　灌溉方式和施氮量对不同品种直播稻抽穗期叶面积指数的影响

Fig. 1　Effects of irrigation managements and nitrogen rates on leaf area index of different varieties of direct-seeded rice at heading stage

W1: 2 叶 1 心至成熟期保持 1~3 cm 的水层; W2: 播种后第 64 d 至成熟期, 每次灌水 2~3 cm, 当土壤水势(ψ_{soil})为−15 kPa 时, 再灌水 2~3 cm, 如此循环; W3: 播种后 64 d 至成熟期, 每次灌水 2~3 cm, 当土壤水势(ψ_{soil})为−30 kPa 时, 再灌水 2~3 cm, 如此循环; N0: 不施用氮肥; N120: 施氮量为 120 kg·hm^{-2}; N180: 施氮量为 180 kg·hm^{-2}; N240: 施氮量为 240 kg·hm^{-2}。不同小写字母表示同一灌溉方式下, 不同施氮量间差异显著。W1: soil surface water layer was kept at 1−3 cm from 2.1 leaves to maturity; W2: soil surface water layer was added to 2−3 cm when the soil water potential (ψ_{soil}) reached −15 kPa

from 64 days after sowing to mature stage; W3: soil surface water layer was added to 2–3 cm when the soil water potential (ψ_{soil}) reached –30 kPa from 64 days after sowing to mature stage. N0: no nitrogen fertilizer; N120: N rate was 120 kg·hm^{-2}; N180: N rate was 180 kg·hm^{-2}; N240: N rate was 240 kg·hm^{-2}. Different lowercases letters indicate significant differences at 0.05 level among different nitrogen rates under the same irrigation management.

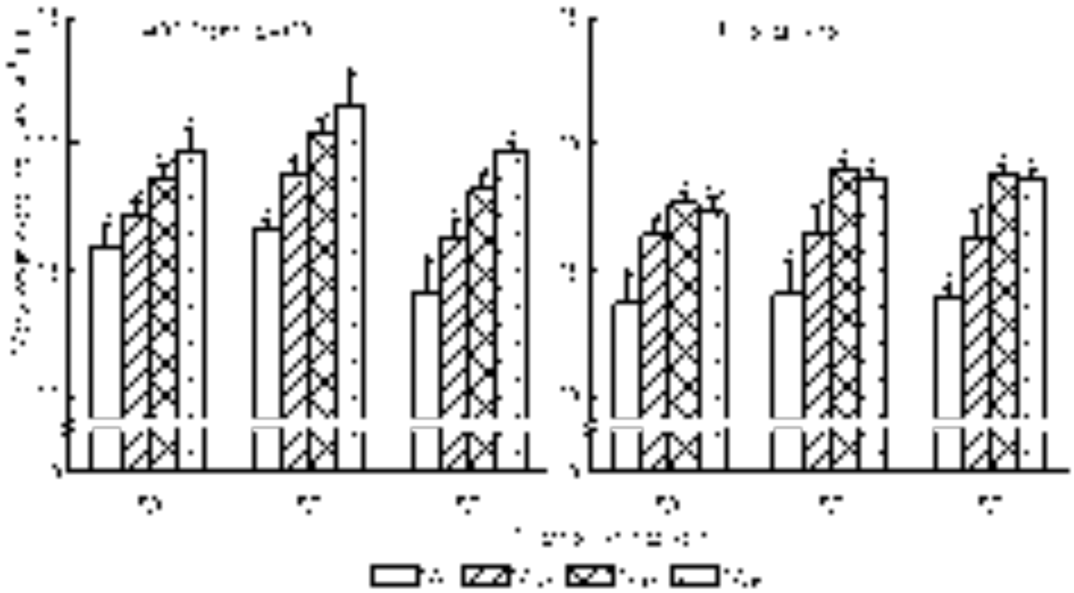

图 2　灌溉方式和施氮量对不同品种直播稻抽穗期剑叶光合速率的影响

Fig. 2　Effects of irrigation managements and nitrogen rates on photosynthetic rate in flag leaves of different varieties of direct-seeded rice at heading

W1: 2 叶 1 心至成熟期保持 1~3 cm 的水层; W2: 播种后第 64 d 至成熟期，每次灌水 2~3 cm，当土壤水势(ψ_{soil})为–15 kPa 时，再灌水 2~3 cm，如此循环; W3: 播种后 64 d 至成熟期，每次灌水 2~3 cm，当土壤水势(ψ_{soil})为–30 kPa 时，再灌水 2~3 cm，如此循环; N0: 不施用氮肥; N120: 施氮量为 120 kg·hm^{-2}; N180: 施氮量为 180 kg·hm^{-2}; N240: 施氮量为 240 kg·hm^{-2}。不同小写字母表示同一灌溉方式下，不同施氮量间差异显著。W1: soil surface water layer was kept at 1–3 cm from 2.1 leaves to maturity; W2: soil surface water layer was added to 2–3 cm when the soil water potential (ψ_{soil}) reached –15 kPa from 64 days after sowing to mature stage; W3: soil surface water layer was added to 2–3 cm when the soil water potential (ψ_{soil}) reached –30 kPa from 64 days after sowing to mature stage. N0: no nitrogen fertilizer; N120: N rate was 120 kg·hm^{-2}; N180: N rate was 180 kg·hm^{-2}; N240: N rate was 240 kg·hm^{-2}. Different lowercases letters indicate significant differences at 0.05 level among different nitrogen rates under the same irrigation management.

2.3　灌溉方式和施氮量对直播稻干物质积累的影响

从表 2 看，灌溉方式和施氮量对直播稻干物质积累的影响因品种的不同存在显著差异。对‘德香 4103’而言，常规灌溉方式下有利于拔节前以及抽穗后干物质积累量的增加，从而提高最终生物产量，但收获指数显著降低；采用干湿交替灌溉后减少灌溉水量虽有利于提高拔节至抽穗期间的干物质积累量，但拔节前及抽穗后干物质积累量显著减少，导致生物量降低的同时收获指数减少。不同灌溉方式下适当增施氮肥实现干物质积累量提高的途径并不一致，表现为常规灌溉和重干湿交替灌溉方式下适当增施氮肥(施氮量分别为 180 kg·hm^{-2} 和 240 kg·hm^{-2})有利于提高抽穗后干物质积累量，轻干湿交替灌溉方式下适当增施氮肥(240 kg·hm^{-2})有利于提高拔节至抽穗、抽穗后干物质积累量。对‘金农丝苗’而言，常规灌溉和轻干湿交替灌溉方式下最终生物产量和收获指数均显著高于重干湿交替灌溉方式，二者最终生物产量优势分别在于拔节前和拔节至抽穗期干物质积累量的提高；常规灌溉和轻干湿交替灌溉方式下适当增施氮肥(施氮量分别为 240 kg·hm^{-2} 和 180 kg·hm^{-2})有利于增加拔节前及抽穗后干物质积累量，最终生物产量和收获指数显著提高；而重干湿交替灌溉方式下适当增施氮肥(施氮量为 240 kg·hm^{-2})有利于提高拔节至抽穗及抽穗后干物质积累量，最终生物产量和收获指数显著提高。这表明直播稻灌溉方式改变后，各生育阶段干物质积累对最终生物产量的贡献存在差异。

表 2　灌溉方式和施氮量对不同品种直播稻干物质积累的影响

Table 2　Effects of irrigation managements and nitrogen rates on biomass accumulation of different varieties of direct-seeded rice

品种	灌溉方式	施氮量	干物质积累量 Dry matter accumulation (t·hm^{-2})	收获指数

			拔节前 Before jointing	拔节—抽穗 Jointing -heading	抽穗—成熟 Heading–maturity	成熟期 Maturity	
德香 4103 Dexiang4103	W1	0	3.31±0.03d	5.34±0.34cd	1.84±0.24e	10.49±0.24f	0.520±0.012bcd
		120	4.59±0.37bc	5.42±0.12e	3.40±0.66b	13.41±0.66c	0.547±0.028abcd
		180	5.95±0.96a	4.48±0.17f	4.60±025a	15.04±0.25a	0.536±0.009cd
		240	6.29±0.34a	4.85±0.34e	3.93±0.23b	15.06±0.23b	0.515±0.008d
	平均 Average		5.04	5.02	3.44	13.50	0.530
	W2	0	2.58±0.05e	5.12±0.23de	1.95±0.48e	9.65±0.48g	0.546±0.027a
		120	4.40±0.47c	5.99±0.84bc	3.55±0.16d	13.93±0.16d	0.549±0.006a
		180	5.12±0.32b	5.73±0.16cd	5.22±0.63c	16.07±0.63c	0.537±0.021abc
		240	4.27±0.24c	6.34±0.12bc	4.98±0.63b	15.59±0.63b	0.517±0.200abc
	平均 Average		4.09	5.80	3.93	13.81	0.537
	W3	0	2.20±0.12e	4.70±0.12ef	1.15±0.15e	8.05±0.15h	0.575±0.011a
		120	3.42±0.08d	6.61±0.29ab	1.44±0.70e	11.48±0.70e	0.551±0.033abc
		180	3.29±0.60d	7.08±0.32a	1.53±0.70e	11.91±0.70e	0.560±0.033ab
		240	3.26±0.04d	6.56±0.08ab	4.55±0.14b	14.37±0.14c	0.546±0.005abcd
	平均 Average		3.04	6.24	2.17	11.45	0.558
金农丝苗 Jinnongsimiao	W1	0	3.93±0.14f	4.01±0.55f	2.18±0.40bc	10.12±0.40c	0.540±0.022bc
		120	4.20±0.47ef	5.59±0.77bc	3.82±0.23ab	13.62±0.23b	0.536±0.009abc
		180	7.24±0.16b	3.29±0.42g	4.04±0.87a	14.57±0.87ab	0.540±.033abc
		240	7.69±0.32a	3.74±0.12e	3.39±0.66bc	14.82±0.66ab	0.508±0.023c
	平均 Average		5.76	4.16	3.36	13.28	0.531
	W2	0	2.38±0.12h	5.42±0.35bc	2.32±0.05c	10.12±0.05c	0.525±0.003bc
		120	3.33±0.28g	6.65±0.28a	3.99±0.77ab	13.98±0.77ab	0.544±0.031abc
		180	5.07±0.19c	5.18±0.12bc	4.21±0.34ab	14.46±0.34ab	0.557±0.013ab
		240	4.88±0.42cd	5.24±0.31bcd	4.99±0.54a	15.11±0.54a	0.542±0.019abc
	平均 Average		3.92	5.63	3.88	13.42	0.542
	W3	0	2.43±0.03h	4.87±0.58d	1.54±0.61c	8.85±0.61c	0.559±0.040abc
		120	3.23±0.25g	6.10±0.57ef	3.74±0.53a	13.07±0.53b	0.582±0.023abc
		180	4.60±0.08de	5.19±0.20cd	4.37±1.59a	14.15±1.59ab	0.588±0.067a
		240	4.51±0.29de	5.65±0.15b	3.94±0.57a	14.10±0.57ab	0.562±0.022abc
	平均 Average		3.69	5.45	3.40	12.54	0.573
F 值 *F*-value	品种 Variety (V)		13.41	18.09	42.11*	8.39	20.70*
	灌溉方式 Irrigation management (I)		359.60**	74.50**	53.07**	128.55**	42.91**
	施氮量 Nitrogen rate (N)		204.88**	5.70*	23.69**	27.58**	1.49
	V × I		20.88**	32.91**	49.83**	237.90**	2.08
	V × N		20.73**	13.22*	3.52*	1.66	0.51
	I × N		15.28**	10.49**	2.91*	1.59	0.14
	V × I × N		0.65	3.93**	3.98**	2.75*	0.76

W1: 2 叶 1 心至成熟期保持 1~3 cm 水层; W2: 播种后 64 d 至成熟期，每次灌水 2~3 cm，当土壤水势(ψ_{soil})为−15 kPa 时，再灌水 2~3 cm，如此循环; W3: 播种后 64 d 至成熟期，每次灌水 2~3 cm，当土壤水势(ψ_{soil})为−30 kPa 时，再灌水 2~3 cm，如此循环。同列不同小写字母表示同一品种不同灌溉方式和施氮量组合差异显著(P<0.05)。*和**分别表示在 0.05 和 0.01 水平上差异显著。W1: soil surface water layer was kept at 1–3 cm from 2.1 leaves to maturity; W2: soil surface water layer was added to 2–3 cm when the soil water potential (ψ_{soil}) reached −15 kPa from 64 days after sowing to mature stage; W3: soil surface water layer was added to 2–3 cm when the soil water potential (ψ_{soil}) reached −30 kPa from 64 days after sowing to mature stage. Different lowercases letters in the same column indicate significant differences at 0.05 level among different interaction combinations of irrigation managements and nitrogen rates of a variety. * and ** mean significant difference at 0.05 and 0.01 levels, respectively.

2.4 灌溉方式和施氮量对直播稻氮素积累及转运的影响

由表 3 可知，不同灌水处理除对茎鞘转运量无显著影响外，灌水和施氮处理对氮素积累、转运均有显著或极显著影响，且对抽穗期、成熟期氮素积累量、叶片转运量、穗部氮增加量具有极显著的互作效应。两品种抽穗期氮素积累量存在显著差异，‘金农丝苗’显著高于‘德香 4103’，且水氮处理对两个品种氮素积累量影响趋势存在差异。‘德香 4103’抽穗期及成熟期氮素积累量均随灌水量减少而先升高后降低，随施肥量增加而显著升高。‘金农丝苗’抽穗期氮素积累量随灌水量减少而呈下降趋势，其成熟期氮素积累量受灌水量影响与‘德香 4103’成熟期氮素积累量变化趋势相同。但在轻干湿交替灌溉处理下，‘金农丝苗’抽穗期及成熟期氮素积累量随施氮量增加而先上升后下降，在 N180 处理下达最大值。浅水灌溉、重干湿交替处理下氮素积累量均随施氮量增加而提高，与‘德香 4103’表现一致。两个直播稻收获指数均随灌水量减少而增大，

随施肥量增加而减小。灌水处理对两个直播稻的叶片、茎鞘氮素转运量及穗部氮增加量影响一致，均随灌水量增加而呈先升后降的趋势，在轻干湿交替灌溉处理下，3 个指标均达最大值，说明适度水分胁迫促进了氮素向穗部转移。在轻干湿交替灌溉处理中，'德香 4103'在 N240 处理下叶片、茎鞘氮素转运量及穗部氮增加量均显著高于其余施氮处理，而'金农丝苗'则在 N180 处理下显著高于其余施氮处理，说明对氮素转运、利用存在品种差异。两个直播稻的叶片转运率、茎鞘转运率、氮转运贡献率在各个水氮处理下表现相同，均随灌水量减少而提高，随施氮量增加而降低。

表 3　灌溉方式和施氮量对不同品种直播稻氮素积累及转运的影响

Table 3　Effects of irrigation managements and nitrogen rates on nitrogen accumulation and translocation of different varieties of direct-seeded rice

品种 Variety	灌溉方式 Irrigation management	施氮量 Nitrogen rate (kg·hm^{-2})	氮素积累量 N accumulation (kg·hm^{-2})		氮收获指数 N harvest index	叶片转运量 Translocation amount of Leaf (kg)	叶片转运率 Translocation ratio of leaf (%)	茎鞘转运量 Translocation amount of stem-sheath (kg)	茎鞘转运率 Translocation ratio of stem-sheath (%)	穗部氮增加量 Increment of panicle nitrogen (kg)	氮转运贡献率 N translocation conversion rate (%)
			抽穗期 Heading	成熟期 Maturity							
德香 4103 Dexiang 4103	W1	0	72.29±5.71f	87.62±2.25e	73.75±0.66abc	23.38±0.43d	70.46±1.29bcd	12.24±0.41cde	48.14±1.63ab	50.95±0.61f	69.92±0.05bc
		120	92.19±3.28e	117.74±1.51cd	72.45±2.24bc	32.28±0.48c	70.05±1.04cde	12.68±1.86cde	40.51±5.94cd	70.50±1.49e	63.76±3.17de
		180	107.81±5.14c	136.65±5.52b	69.28±3.09de	35.43±1.14b	65.26±2.09e	13.01±1.36bcde	36.13±3.79de	77.28±2.17c	62.68±3.17de
		240	109.50±3.17b	148.37±0.55b	67.25±2.29e	28.16±2.08c	55.88±4.12f	10.15±1.3de	27.83±3.64e	77.16±2.00e	49.64±4.41e
	平均 Average		95.45	122.59	70.69	29.81	65.41	12.02	38.15	68.97	61.50
	W2	0	63.17±3.02g	76.09±5.02f	75.35±1.67ab	21.71±0.07d	75.03±0.23ab	10.77±0.54e	48.40±2.43ab	45.40±1.18g	71.54±1.29ab
		120	94.68±5.92e	119.49±2.97cd	73.21±0.77abc	35.51±0.30b	74.21±0.64abc	12.91±1.92bcde	39.62±5.88cd	73.23±1.07d	66.13±2.34cd
		180	121.12±3.42c	142.78±5.80b	71.02±1.52cd	41.84±1.49b	69.32±2.48de	19.37±1.01bc	45.93±2.40cde	82.87±0.35b	73.87±0.72de
		240	111.92±3.04a	150.88±3.26a	70.72±3.04cd	35.89±3.33a	63.56±5.90de	13.78±2.37a	36.86±6.35cde	88.62±0.98a	56.04±5.18de
	平均 Average		97.72	122.31	72.57	33.74	70.53	14.21	42.70	72.53	66.90
	W3	0	59.41±1.29g	69.80±1.34f	75.88±1.18a	20.98±0.08d	76.15±0.30a	10.80±0.67e	51.29±3.17a	42.18±1.95h	75.36±1.78a
		120	95.29±1.65e	115.74±8.43d	73.80±1.14abc	36.27±0.49b	75.42±1.01a	13.80±0.41bcd	42.80±1.28bc	70.53±0.91e	71.00±1.28ab
		180	103.01±3.16d	122.72±5.06c	71.85±0.54bc	36.38±1.29b	70.11±2.48cd	14.27±0.80bcd	42.86±2.40bc	70.36±0.84d	71.98±1.13bc
		240	110.52±0.85c	151.10±3.60b	70.32±1.08cd	36.09±0.71b	63.56±1.24de	12.77±1.95b	34.56±5.28cd	89.44±1.64b	54.62±2.96de
	平均 Average		92.06	114.84	72.96	32.43	71.31	12.91	42.87	68.13	68.24
金农丝苗 Jinnongsimiao	W1	0	74.04±5.35f	89.47±5.23f	73.99±1.23abc	26.94±0.43f	74.65±1.18ab	9.08±0.19e	39.19±0.81bc	51.44±0.91h	70.01±0.84bc
		120	99.00±6.04d	122.49±1.02de	72.93±0.83bc	35.98±0.90de	71.34±1.79bcd	11.60±1.37bcd	38.28±4.53bc	71.07±0.88f	66.95±1.09cde
		180	113.25±2.83c	141.16±9.81b	71.51±1.17c	39.50±2.97bc	68.13±5.13cd	13.04±1.29b	37.46±3.71bc	80.45±0.60c	65.31±4.94e
		240	128.31±7.85a	157.85±4.34a	71.08±1.69c	41.73±2.47b	67.08±3.97d	13.82±3.40ab	35.48±8.74c	85.08±1.17b	65.28±1.94e
	平均 Average		103.65	127.74	72.38	36.04	70.30	11.88	37.60	72.01	66.89
	W2	0	72.30±7.15f	87.08±0.93f	74.50±1.04ab	25.85±0.94fg	74.49±2.70ab	10.50±0.26cde	44.04±1.09ab	51.14±1.15h	71.09±1.33ab
		120	103.43±2.41d	127.83±10.90cd	72.91±2.06bc	36.00±0.27de	72.25±0.55abc	13.68±0.4ab	39.85±1.29bc	74.08±0.38e	67.07±0.60cde
		180	111.93±2.71b	138.38±3.22a	72.10±0.63bc	37.49±1.80a	68.99±3.32cd	13.17±1.69a	36.55±4.70bc	77.11±0.90a	65.69±0.14de
		240	119.05±6.48c	152.97±3.85bc	71.19±0.99c	38.04±1.20cd	66.54±2.10cd	13.80±1.04b	35.645±2.69c	85.76±1.01d	60.45±0.58e
	平均 Average		101.68	126.57	72.68	34.34	70.57	12.79	39.02	72.02	66.07
	W3	0	65.81±6.93g	77.89±6.48f	75.88±1.87a	24.09±0.47g	76.12±1.50a	10.06±0.52de	47.39±2.46a	46.23±1.13i	73.86±1.41a
		120	93.47±7.23e	114.03±6.00e	73.18±1.93abc	33.64±0.57e	74.53±1.25ab	12.90±1.07bc	40.42±3.34bc	67.10±0.37g	69.35±1.37bcd
		180	101.42±1.45d	125.68±16.67cde	72.56±3.55bc	36.54±0.81d	72.26±1.61abc	13.39±1.07ab	40.02±3.19bc	74.19±0.04e	67.30±0.95cde
		240	103.02±1.83d	131.27±5.41cd	73.07±0.22bc	36.67±1.02d	71.37±1.99bcd	13.68±1.45ab	39.87±4.22bc	78.56±0.91e	64.06±1.52cde
	平均 Average		90.93	112.22	73.67	32.73	73.57	12.51	41.93	66.53	68.64
F 值 *F*-value	品种 Variety (V)		48.55*	3.09	7.81	155.11**	178.54**	301.21**	503.40**	0.31	305.77**
	灌溉方式 Irrigation management (I)		94.03**	72.76**	5.43*	43.95**	31.05**	4.17	5.15*	230.86**	20.94**

施氮量 Nitrogen rate (N)	1042.89**	319.31**	20.37**	336.42**	28.87**	28.06**	20.38**	4047.62**	40.07**
V × I	2.26	7.69*	1.15	42.35**	3.99	0.08	0.06	62.59**	3.24
V × N	25.09**	7.37**	1.59	6.90**	2.90*	1.43	2.18	100.82**	2.76
I × N	19.85**	4.32**	0.32	8.13**	0.24	1.35	0.38	85.36**	0.34
V × I × N	20.46**	10.90**	0.29	19.44**	0.22	4.21**	0.72	202.55**	0.38

W1: 2 叶 1 心至成熟期保持 1~3 cm 水层; W2: 播种后 64 d 至成熟期，每次灌水 2~3 cm，当土壤水势(ψ_{soil})为−15 kPa 时，再灌水 2~3 cm，如此循环; W3: 播种后 64 d 至成熟期，每次灌水 2~3 cm，当土壤水势(ψ_{soil})为−30 kPa 时，再灌水 2~3 cm，如此循环。同列不同小写字母表示同一品种不同灌溉方式和施氮量组合差异显著(P<0.05)。*和**分别表示在 0.05 和 0.01 水平上差异显著。W1: soil surface water layer was kept at 1−3 cm from 2.1 leaves to maturity; W2: soil surface water layer was added to 2−3 cm when the soil water potential (ψ_{soil}) reached −15 kPa from 64 days after sowing to mature stage; W3: soil surface water layer was added to 2−3 cm when the soil water potential (ψ_{soil}) reached −30 kPa from 64 days after sowing to mature stage. Different lowercases letters in the same column indicate significant differences at 0.05 level among different interaction combinations of irrigation managements and nitrogen rates of a variety. * and ** mean significant difference at 0.05 and 0.01 levels, respectively.

从图 3 可知，成熟期不同部位的氮素积累量存在差异。‘德香 4103’茎鞘、叶片氮素积累量随灌水量减少而减少，随施氮量增加而增加；籽粒氮素积累量随灌水量减少而呈先上升后下降的趋势，在轻干湿交替灌溉下，N120、N180、N240 均高于其余两个灌水处理。‘金农丝苗’茎鞘氮素积累量随灌水量减少先上升后下降，随施氮量增加而增加，在轻干湿交替灌溉下，N120、N180、N240 处理高于其他两个灌水处理；叶片氮素积累量随灌水量减少而减少，随施氮量增加而增加；籽粒氮素积累量随灌水量减少而先上升后下降，随施氮量增加而增加，在轻干湿交替灌溉下，N120、N180 处理氮素积累高于其他处理。说明轻干湿交替灌溉增加了成熟期穗部氮素积累量。

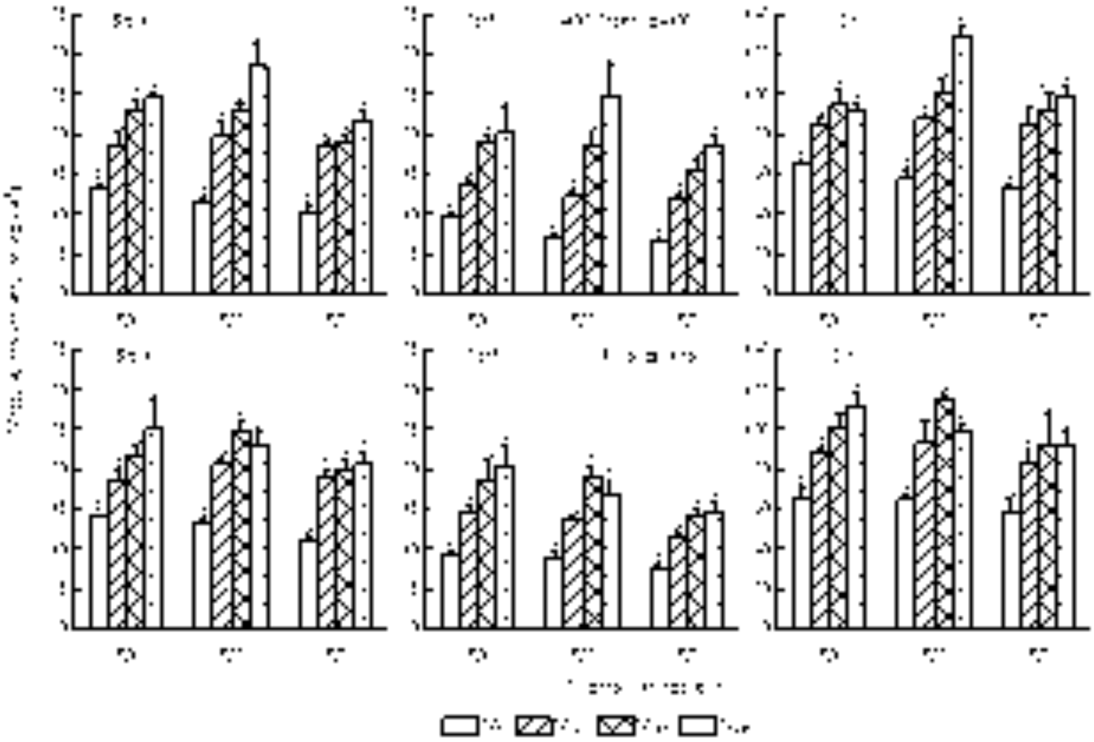

图 **3**　灌溉方式和施氮量对成熟期茎、叶、籽粒氮素积累的影响

Fig. 3　Effects of irrigation managements and nitrogen rates on nitrogen accumulation in stem, leaf and grain of different varieties of direct-seeded rice at maturity

W1: 2 叶 1 心至成熟期保持 1~3 cm 的水层; W2: 播种后第 64 d 至成熟期，每次灌水 2~3 cm，当土壤水势(ψ_{soil})为−15 kPa 时，再灌水 2~3 cm，如此循环; W3: 播种后 64 d 至成熟期，每次灌水 2~3 cm，当土壤水势(ψ_{soil})为−30 kPa 时，再灌水 2~3 cm，如此循环; N0: 不施用氮肥; N120: 施氮量为 120 kg·hm^{-2}; N180: 施氮量为 180 kg·hm^{-2}; N240: 施氮量为 240 kg·hm^{-2}。不同小写字母表示同一灌溉方式下，不同施氮量间差异显著。W1: soil surface water layer was kept at 1−3 cm from 2.1 leaves to maturity; W2: soil surface water layer was added to 2−3 cm when the soil water potential (ψ_{soil}) reached −15 kPa from 64 days after sowing to mature stage; W3: soil surface water layer was added to 2−3 cm when the soil water potential (ψ_{soil}) reached −30 kPa from 64 days after sowing to mature stage. N0: no nitrogen fertilizer; N120: N rate was 120 kg·hm^{-2}; N180: N rate was 180 kg·hm^{-2}; N240: N rate was 240 kg·hm^{-2}. Different lowercases letters indicate significant differences at 0.05 level among different nitrogen rates under the same irrigation management.

2.5　灌溉方式和施氮量对直播稻氮素利用和水分利用率的影响

从表 4 可知，不同灌水和氮肥处理对水稻氮素干物质生产效率、氮素生产效率、氮素农艺效率、氮肥回收效率、水分利用率影响均达显著水平，且互作效应显著。水氮处理对直播稻氮素干物质生产效率影响规律不明显。‘德香 4103’氮素生产效率随灌水量、施氮量增加而降低；‘金农丝苗’氮素生产效率随灌水量增加而增加，在淹灌处理下，其氮素生产效率随施氮量增加而降低，在轻干湿交替处理及重干湿交替处理下，其氮素生产效率随施氮量增加而先降低后上升，说明不同品种氮素生产效率存在差异。两个直播稻氮素农艺效率及氮肥回收效率均随灌水量增加而呈先上升后下降趋势，不同施氮处理对其影响存在差异；各灌水处理下，高施氮处理降低了氮素农艺效率及氮肥回收效率。中低施氮水平下，淹灌、轻干湿交替处理提高了‘德香 4103’的氮素农艺效率及氮肥回收效率，而降低了‘金农丝苗’氮素农艺效率，但差异未达显著水平；在重干湿交替处理下两个品种氮素农艺效率及氮肥回收效率均随施氮量增加而降低，表明在各个灌水处理下，高施氮量反而降低了氮素农艺效率及氮肥回收效率。‘德香 4103’和‘金农丝苗’的水分利用率随着灌水量

的增加而降低，随着施氮量的增加而增加。此外，在轻干湿交替处理下，‘德香 4103’在 N240 处理下、‘金农丝苗’在 N180 处理下氮肥回收效率均超过了 40%，显著高于其余处理。

表 4　灌溉方式和施氮量对不同品种直播稻氮素利用、水分利用率的影响

Table 4　Effects of irrigation managements and nitrogen rates on nitrogen use efficiency and water use efficiency of different varieties of direct-seeded rice

品种 Variety	灌溉方式 Irrigation management	施氮量 Nitrogen rate ($kg\cdot hm^{-2}$)	氮素干物质生产效率 Nitrogen dry matter production efficiency ($kg\cdot kg^{-1}$)	氮素稻谷生产效率 N grain production efficiency ($kg\cdot kg^{-1}$)	氮素农艺效率 Nitrogen agronomic efficiency ($kg\cdot kg^{-1}$)	氮肥回收效率 Nitrogen recovery efficiency (%)	水分利用率 Water use efficiency ($kg\cdot kg^{-1}$)
德香 4103 Dexiang 4103	W1	0	1.20±0.03ab	49.29±2.58b			0.69±0.04i
		120	1.14±0.06ab	48.38±1.49b	17.22±2.19ab	25.1±1.87e	0.87±0.03g
		180	1.11±0.02a	47.03±1.93bc	17.57±2.20ab	27.24±1.25de	1.02±0.04cde
		240	1.02±0.02abc	40.22±1.12de	10.30±1.04c	25.42±0.12f	0.93±0.03f
	平均 Average		1.11	46.23	15.03	25.92	0.88
	W2	0	1.27±0.06ab	54.05±0.9a			0.77±0.01h
		120	1.17±0.01c	45.63±1.17cd	16.75±1.75ab	36.16±4.18b	1.01±0.03de
		180	1.13±0.04d	46.41±0.87cd	20.94±1.03a	37.05±2.79b	1.27±0.02a
		240	1.03±0.04f	42.36±1.09f	14.24±1.03b	28.77±3.12a	1.23±0.03b
	平均 Average		1.15	47.11	17.31	33.99	1.07
	W3	0	1.15±0.02bc	53.69±3.46a			0.74±0.05h
		120	0.99±0.06de	44.34±0.82cd	17.31±1.18ab	38.28±1.12b	1.00±0.02e
		180	0.97±0.06e	42.10±1.15e	11.82±1.18c	29.40±0.74c	1.04±0.03cd
		240	0.95±0.01d	35.42±1.02f	10.03±0.97c	34.05±1.26cd	1.05±0.03c
	平均 Average		1.02	43.88	13.05	33.91	0.96
金农丝苗 Jinnongsimiao	W1	0	1.14±0.04ab	48.10±1.09bc			0.71±0.02h
		120	1.11±0.02abc	45.61±0.98ef	16.03±1.50bc	27.52±4.36c	0.93±0.02f
		180	1.03±0.06c	43.65±1.19f	15.48±1.40cd	28.72±2.91c	1.00±0.03e
		240	0.94±0.04d	39.64±0.32g	12.20±0.32e	28.67±1.89c	1.04±0.01d
	平均 Average		1.05	44.25	14.57	28.30	0.92
	W2	0	1.16±0.01ab	49.29±1.64b			0.87±0.03g
		120	1.09±0.06bc	45.83±0.63de	19.58±1.01a	33.96±0.77b	1.17±0.02c
		180	1.04±0.02d	46.07±1.37g	17.58±1.58ab	28.50±0.52a	1.30±0.04a
		240	0.99±0.03bc	44.23±0.99cde	15.46±0.95de	27.87±1.65de	1.33±0.03a
	平均 Average		1.07	46.35	17.46	30.11	1.17
	W3	0	1.14±0.08a	54.05±1.32a			0.88±0.02g
		120	1.15±0.05a	47.99±0.87bcd	15.82±1.24c	30.12±5.40bc	1.15±0.02c
		180	1.13±0.13abc	46.43±1.19cde	13.57±1.25cde	26.55±3.60cd	1.23±0.03b
		240	1.07±0.04ab	45.71±0.99cde	11.21±0.44e	20.75±2.54e	1.22±0.01b
	平均 Average		1.12	48.53	13.54	25.81	1.12
F 值 F-value	品种 Variety (V)		3.37	2.39	0.00	56.58^{*}	214.91^{**}
	灌溉方式 Irrigation management (I)		85.93^{**}	19.98^{**}	42.47^{**}	25.89^{**}	389.99^{**}
	施氮量 Nitrogen rate(N)		26.65^{**}	259.92^{**}	46.53^{**}	47.14^{**}	676.55^{**}
	V × I		275.58^{**}	173.36^{**}	0.59	12.83^{**}	29.30^{**}
	V × N		1.83	31.99^{**}	0.06	20.35^{**}	4.66^{**}
	I × N		5.11^{**}	12.97^{**}	3.63^{*}	14.22^{**}	17.89^{**}
	V × I × N		9.13^{**}	20.46^{**}	4.14^{*}	31.08^{**}	3.45^{**}

W1: 2 叶 1 心至成熟期保持 1~3 cm 水层; W2: 播种后 64 d 至成熟期，每次灌水 2~3 cm，当土壤水势(ψ_{soil})为−15 kPa 时，再灌水 2~3 cm，如此循环; W3: 播种后 64 d 至成熟期，每次灌水 2~3 cm，当土壤水势(ψ_{soil})为−30 kPa 时，再灌水 2~3 cm，如此循环。同列不同小写字母表示同一品种不同灌溉方式和施氮量组合差异显著($P<0.05$)。*和**分别表示在 0.05 和 0.01 水平上差异显著。W1: soil surface water layer was kept at 1−3 cm from 2.1 leaves to maturity; W2: soil surface water layer was added to 2−3 cm when the soil water potential (ψ_{soil}) reached −15 kPa from 64 days after sowing to mature stage; W3: soil surface water layer was added to 2−3 cm when the soil water potential (ψ_{soil}) reached −30 kPa from 64 days after sowing to mature stage. Different lowercases letters in the same column indicate significant differences at 0.05 level among different interaction combinations of irrigation managements and nitrogen rates of a variety. * and ** mean significant difference at 0.05 and 0.01 levels, respectively.

3　讨论

根系是植株吸收水分及养分的重要器官。有研究表明，控制灌溉可不同程度提高水稻根系活力、最长

根长、根直径、根体积[24]，提高稻基农田土壤酶活性、微生物量碳氮[25]，改善水稻根际土壤环境，加快水稻根系泌氧，促进根系生长[26]，同时还提高氮代谢酶活性[27]，促进对氮素吸收、转运、利用。本研究表明，轻干湿交替灌溉处理促进了直播稻氮素吸收、积累，同时促进了叶片、茎鞘氮素转运量，但叶片转运率、茎鞘转运率、氮素转运贡献率不及重干湿交替灌溉处理。可以看出，直播稻受水分胁迫越重时，氮素吸收越受影响，穗部氮素则主要靠叶片、茎鞘部等营养器官向穗部转运来保证，这与王绍华等[18]研究结果一致。从施氮量来看，氮肥用量较低时，直播稻氮素积累量少，但其叶片、茎鞘转运率更高，氮转运贡献率亦更高。水、氮两因素对氮素积累及转运过程中受施氮量影响比灌水处理更大。轻干湿交替灌溉处理能提高氮素农艺效率及氮肥回收效率，但氮素生产效率因品种影响存在差异，水分胁迫降低了‘德香 4103’氮素生产效率，而提高了‘金农丝苗’氮素生产效率。施氮量越高反而降低了氮素生产效率，可能是高施氮量虽然增加了氮素积累，但茎、叶氮素向穗部转运降低，在营养器官中滞留较多，产生了较大的浪费[18]。轻干湿交替灌溉处理下，适度提高氮肥用量可以提高氮素农艺效率及回收效率，但差异不明显，过高则会降低氮素生产效率，且重干湿交替灌溉下，施氮量增加降低了氮素利用效率。

有研究表明，干湿交替灌溉有利于提高水稻剑叶光合速率，且在抽穗期提高氮肥用量(180~270 kg·hm^{-2})可增加剑叶光合速率[28]。本研究结果与此一致，轻干湿交替灌溉提高了抽穗期剑叶光合速率，且其随施氮量增加而呈上升趋势。同时，灌水量减少显著降低了 LAI，但施氮水平提高可显著增加 LAI。施氮对产量及其构成因素均有极显著影响，灌水对有效穗、结实率及产量有极显著影响，施氮量影响大于灌水。水氮互作效应对直播稻产量、结实率影响显著。孙永健等[15]指出水氮互作对穗粒数、产量有显著影响，而在本研究结果中，水氮互作对结实率及产量产生了显著影响，可能是不同品种在不同环境下对水氮互作响应存在差异。说明在本研究中水氮互作下产量的提高来源是结实率的显著提升。付景等[11]研究表明，轻干湿交替灌溉处理可以提高抗氧化酶活性，提高超级稻根系中细胞分裂素(Z+ZR)和吲哚-3-乙酸(IAA)含量，在生理基础上对不利环境做出响应，最终提高结实率，促进产量提高。在轻干湿交替灌溉处理下，结实率、产量均高于其余两个灌水处理，适度水分胁迫促进了直播稻产量提高，但在施氮水平上产量高峰出现存在品种差异，在此处理下，‘德香 4103’在 N240、‘金农丝苗’在 N180 下达最高产量。在轻度水分胁迫下，适当增加施氮量可以提高产量，达到“以肥调水”的目的，但不同品种对氮肥耐性有差异。因此，针对不同品种的耐肥力，可采用轻干湿交替灌溉并依据品种特性合理施用氮肥，施用量在 180~270 kg·hm^{-2} 之间，提高氮素农艺效率及回收效率，可达到高产高效。

4 结论

灌溉方式和施氮量对直播稻氮肥利用效率及产量形成存在显著互作效应，合理安排灌溉方式和施氮量可以实现直播稻产量、氮肥利用效率和水分利用率同步提高。从节水增产的角度，轻干湿交替灌溉更适合于直播稻高产、节水、高效栽培，且‘德香 4103’配合施纯氮 240 kg·hm^{-2} 处理产量、氮素利用率和水分利用率最高，‘金农丝苗’配合施纯氮 180 kg·hm^{-2} 处理产量、氮素利用率和水分利用率最高。

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